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Seal Monitoring System for an Explosive Containment Vessel

J. W. Pastrnak, C. D. Henning, V. A. Switzer, W. Grundler, J. R. Holloway, J. J. Morrison, R. S. Hafner

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Authored by: J.W. Pastrnak, C.D. Henning, V.A. Switzer,
W. Grundler, J.R. Holloway, J.J. Morrison, and R.S. Hafner

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Abstract

Researchers at Lawrence Livermore National Laboratory are developing high-performance explosive firing vessels to contain (one time) explosive detonations that contain toxic metals and hazardous gases. The filament-wound polymer composite vessels are designed to contain up to 80 lb (TNT equivalent) explosive in a 2-meter sphere without leakage. So far, two half-scale (1-meter diameter) vessels have been tested; one up to 150% of the design explosive limit. Peak dynamic pressures in excess of 280 MPa (40 Ksi) in the vessel were calculated and measured. Results indicated that there was a small amount of gas and particle leakage past the first two of the seven o-ring seals. However, the remaining five seals prevented any transient leakage of the toxic gases and particulates out of the vessel. These results were later confirmed by visual inspection and particulate analysis of swipes taken from the sealing surfaces.

INTRODUCTION

Lawrence Livermore National Laboratory (LLNL) is collaborating with its sister laboratory, Los Alamos National Laboratory (LANL), to develop a filament-wound composite firing vessel for the containment of explosive experiments containing toxic and possibly radioactive materials. Release of these materials might constitute a health risk. Insuring that releases are below the public and worker exposure limits set the design criteria for these blast containment vessels. The vessels must contain the dynamic blast impulse, the residual gas pressure of the explosive by-products, and the high velocity fragments thrown from metal-cased experiments. Vessel rupture resulting in gross leakage of toxic materials is prevented by a strong Kevlar composite structure wound on an aluminum liner. Also, shrapnel can be kept from penetrating the vessel wall by installing metal or ceramic shielding within the vessel. A complete description of the Composite Vessel Development is given by Pastrnak et al. [1], including explosive experiments conducted with half-scale models vessel prototypes up to 150% of the design load.

The leakage of particulates and gases past the relatively soft O-ring seals at the vessel ports is the focus of this paper. Zero leakage to the outside of a vessel may be unattainable; gases diffuse through seals and even metal. Transient seal motions in explosive containments make it even more difficult to achieve zero leakage. Instead, it was necessary to develop the methods to measure very small leaks that are below environmental risks and consistent with established regulatory standards.

VESSEL AND PORT CONFIGURATION

The CVD (Composite Vessel Development) vessel shown in Figure 1 has a composite structure (Kevlar) with a 2219 -T62 aluminum liner. The liner is used as a winding form; it prevents gas leakage and supports the two polar opening ports.

Figure 1- The half scale (1 meter diameter) composite vessel CVD 2 has a Kevlar structure wound on a 2219-T62 aluminum liner. It uses an HY 100 steel end plug and clamp to support the sequential port seals.

An HY 100 steel plug shown in Figure 2 is inserted into the openings; it contains five dynamic O-rings on the bore of the plug and two static O-rings on the plug face. To prevent debris from damaging the first O-ring a soft 1100-O aluminum wire was helically wound in the space below. The blast pressure integrated over the plug face resulted in a vertical blast force of 30 million newtons that tries to push the plug out of the bore. This force is restrained by a triple segmented HY 100 steel clamp and an outer wedge ring. The wedge ring is preloaded with high strength bolts. The 30 degree teeth on the clamps were designed to cause a radial force outward on the wedge ring and an equal reaction force inward on the aluminum port. This preload compression was enough to press the bore of the aluminum liner elastically against the steel plug. Plastic gauge was used to confirm the closing of the radial gap when the bolts were tightened. During the explosion, still more compression is placed on the seal clearance by the 280Mpa blast pressure helping to minimize the gaps through which the O-ring seal could extrude.

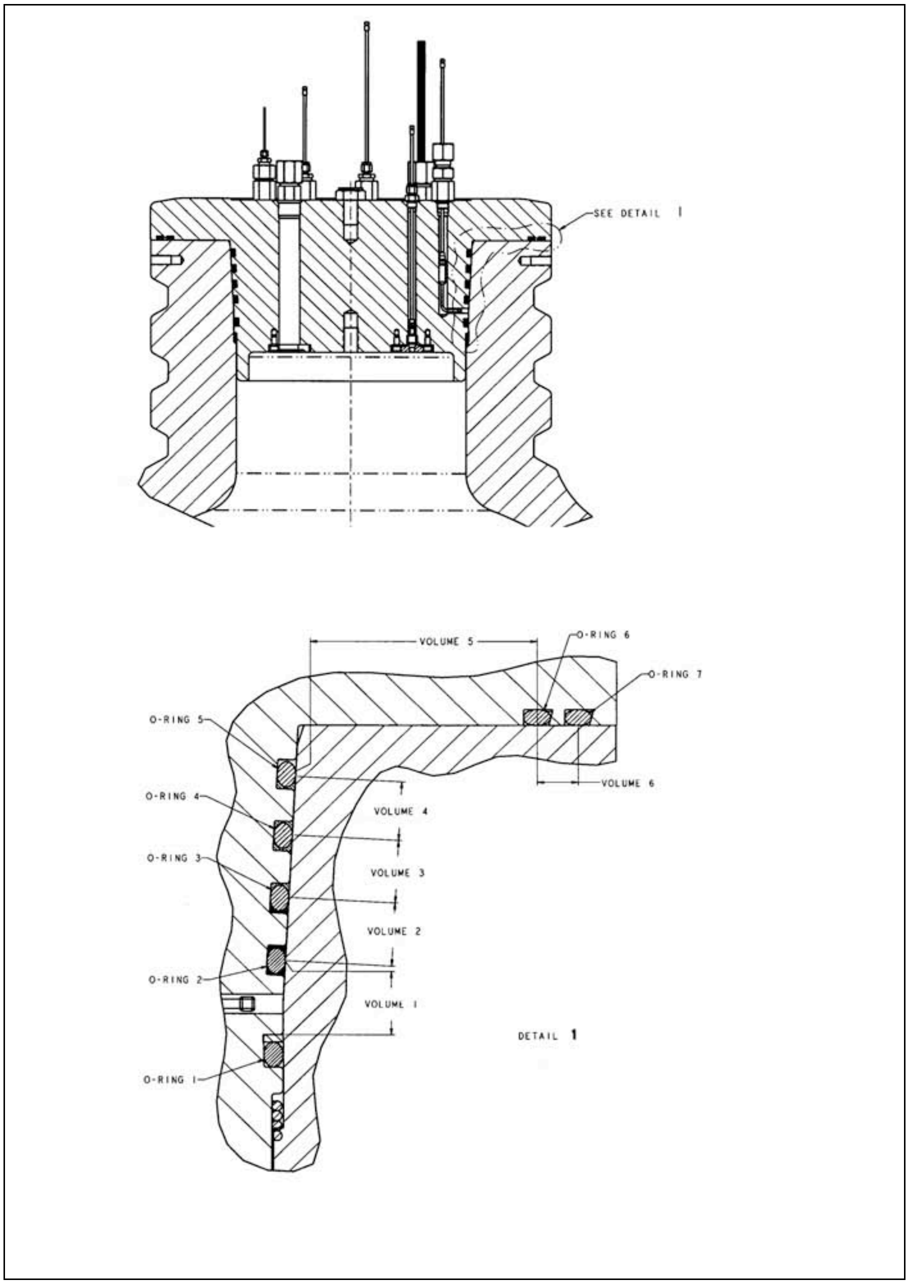

Figure 2a – The O-ring seal interstitial volumes were found to be about 20 cc by design calculations and experimental measurements.

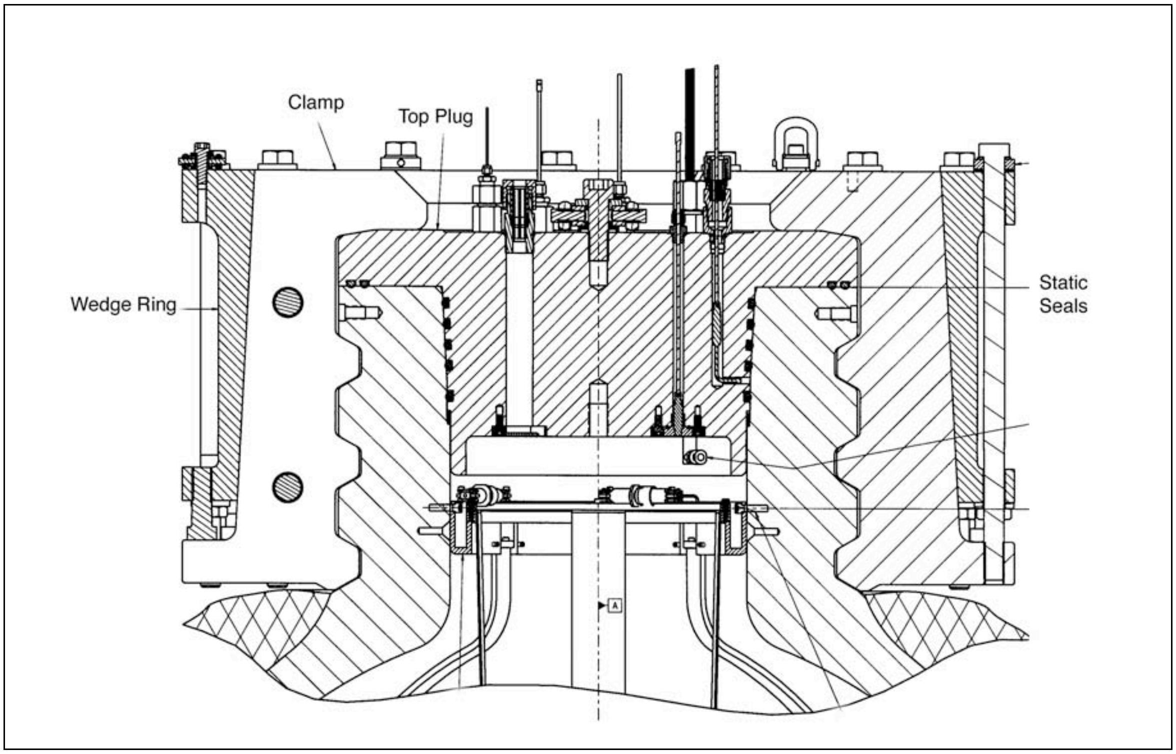

Figure 2b – Section view of top port and clamp assembly.

Radial assembly clearances between the plug and vessel neck were minimized during construction to about .08 mm (3 mils). This was enough clearance to permit assembly by small enough to lessen the tendency of the O-rings to extrude into the plug-to-bore gap under the 280 Mpa (40 Ksi) blast pressure. Clamping forces were used to close the assembly gap. The peak pressure before extrusion of the O-ring into the gap shown in Figure 3b can be doubled by use of a Parbac (Parker backing ring) to 14 MPa (20Ksi). This was consistent with our experiments, since it took two O-rings to contain our peak blast pressure of 280 MPa (40 Ksi) even with the careful control of the gap tolerances and dynamic gap closure.

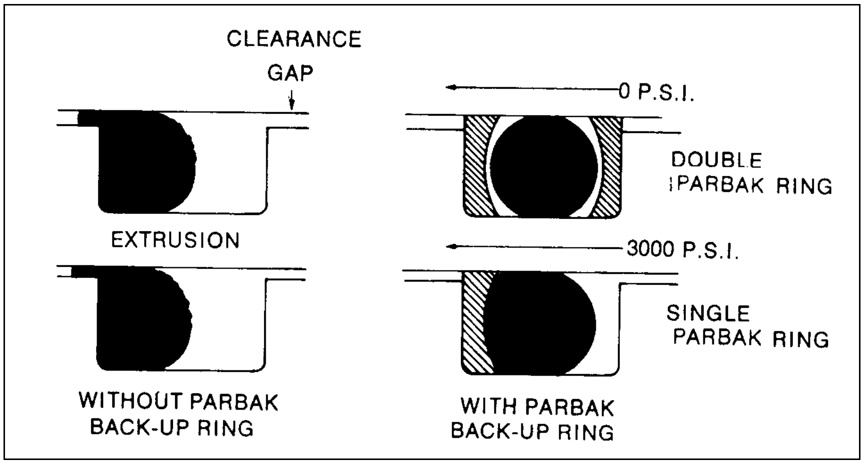

Figure 3a. Seal O-ring extrusion prevented by backing ring. (Parker Seals Handbook ORD 5700)

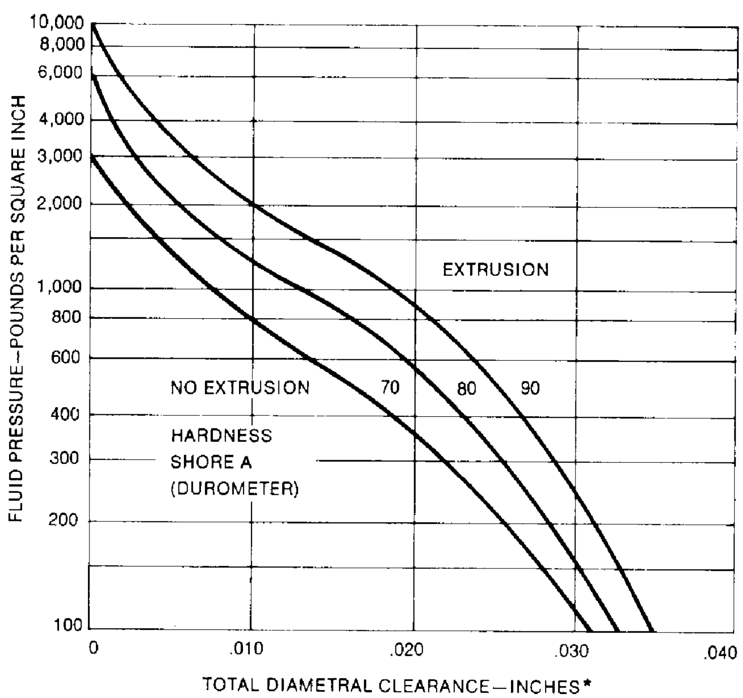

Figure 3b. The harder O-ring material (Shore A 90) and small radial assembly gap permitted pressures up to 70MPa (10 Ksi) before the seals were expected to extrude into the gap. (Parker Seals Handbook ORD 5700)

LEAKAGE CONSIDERATIONS

Transient leakage of hazardous materials such as uranium and beryllium particulates past the port seals needs to be prevented because of potential public and worker environmental hazards. Since no standard design codes exits for blast containment vessels of this type or purpose, we have followed the guidance of related consensus codes. For uranium containment, the ANSI N14.5-1997 Standard for *Leakage Tests on Packages for Shipment of Radioactive Materials* was used as a guide. It defines normal and accident leak rates that are acceptable for nuclear transportation containers. Title 10 Code of Federal Regulations (CFR) Part 71 specifies an allowable release rate for uranium oxide of 2.7 x 10^{-2} Curies in one week. Since the specific activity of ^{233} U is 9.7x10^{-3} Curies/gram, this corresponds to an allowable loss of 2.78 grams in a week. In an accident situation (sudden release) the ANSI Standard appears to amortize the instantaneous leak over a week, as if it were a slower steady state leak. This loss rates is much larger than is not the limiting because that for beryllium in much less.

For beryllium releases, the US Department of Energy (DOE) 10 CFR 850 is used; it places a concentration limit of 2 micrograms per cubic meter of air for worker protection. The DOE Action Level is taken as one tenth of that, so the work place air should be maintained below 0.2 micrograms/cubic meter of beryllium. In the case of surface contamination, 10 CFR 850.30 defines 3 micrograms per 100 sq. cm as the limit; this value is lowered to 0.2 microgram per 100 sq. cm if the part is released to non-beryllium work areas. Thus, the acceptable leak of beryllium (whether spread over a square meter or dispersed in several (5) cubic meters of air is in the range of a microgram.

For either uranium or beryllium, we conclude that if a vessel released no more than one microgram of particulate contaminants during normal firing operations it would be below the worker safety level. Then there would be no need to clean or package the vessel before transporting it to a cleanout or decontamination facility.

Direct measurement of such small amount of particulate contaminants is difficult because they may remain in the seal space or be unevenly distributed on the vessel surfaces. Instead, a gas leakage method is used by the ANSI N14.5 Standard. This maximum uranium U^{233} particulate-to-aerosol concentration of 9 micrograms per cubic centimeter of gas released was experimentally determined by Curren and Bond in the 1980 paper "Leakage of Radioactive Powders from Containers" [2]. Since up to 9 micrograms could be released in 1 cc of gas, if one could detect just 1 microgram, then the gas leakage sensitivity should be about 0.1 cc at standard atmospheric conditions.

Detection of such a small amount of gas can more readily be accomplished by monitoring the small clearance volumes between the O-ring seals on the vessel plugs. Accordingly, small channels were drilled into the top plug for access to the clearance gaps to monitor static differential pressures and argon tracer gas concentrations. The interconnecting capillary tubes, filters and valve spaces were minimized to about 5 cc. The entire O-ring spaces (including joints and valves) was measured to have an approximate volume of 20 cc. [3]. A capillary tube was used to vent this space to a separate 50 cc evacuated sample bottle before and after the blast test. Final pressures in the sample bottles were around 1/3 atmosphere compatible for testing with a mass spectrometer.

If the minimum tolerable leak of 0.1 cc of gas occurred, then the nitrogen in the O-ring interstitial space would be contaminated by the 10% Argon tracer gas from the inside of the vessel to 500 parts per million:

10% argon x 0.1 cc / 20 cc volume = 500 ppm

Since the mass spectrometer we used was capable of resolving 10 ppm, there would be an adequate margin to ensure detection of the Argon from a 0.1 cc leak. This corresponds to detecting a microgram leak of particulates with a margin of safety of 50, or alternately being able to detect 20 nanograms of uranium. Such a leak is well below any of the established Government safety criteria.

EXPERIMENTAL RESULTS

The CVD II vessel was tested to 150% of the blast load (corresponding to an 18 pound TNT equivalent explosive) and produced a peak blast pressure of 280Mpa (40 KSI). To diagnose the leakage past the O-ring seals, small capillary tubes were monitored from each O-ring gap. Initially, this space was filled with pure nitrogen gas, while the full vessel was filled with a mixture of 10% Argon, 20% Oxygen, and 70% nitrogen. Gas samples were taken before (Table I) and after the blast (Table II) to determine if any Argon leaked into the O-ring space. It can be seen in the data that the O-ring spaces were not completely purged of air because a little oxygen (normally 20%) and argon (normally 1%) from the air were still present. Even purging three times with pure nitrogen through the small capillary tube into the dead end O-ring space left small amounts of residual air.

TABLE I -	**GAS SAMPLES (%) TAKEN BEFORE BLAST**				
O-ring space	N_2	O_2	Argon	CO	Hydrocarbons
1 (inside)	99	0.5	0.5	0	0
2	99.7	0.2	0.1	0	0
3	99.7	0.3	0	0	0
4	99.4	0.5	0.1	0	0
5	99.5	0.5	0	0	0
6 (outside)	99.9	0.1	0	0	0

TABLE II - GAS SAMPLES (%) AFTER THE BLAST					
O-ring space	N2	O2	Argon	CO	Hydrocarbons
1 (inside)	32	0.9	2	18	19.9
2	87	3	2	3	2
3	94.9	1.9	2.8	0	0
4	94.8	2.1	1.9	0	0
5	97.4	2.2	0.3	0	0
6 (outside)	95.1	4.6	0.3	0	0

Despite these difficulties with obtaining accurate samples because of inadequate purging and valves, it appears as though the first O-ring definitely leaked. The large amounts of argon, carbon monoxide, and hydrocarbons all indicated significant leakage. Likewise, the second O-ring space had some argon, carbon monoxide and hydrocarbons present. However, the other O-rings did not appear to leak. While there was a small amount of oxygen and argon in these spaces, there was no carbon monoxide or hydrocarbons present from the blast. The argon could be an experimental error or possibly caused by an inward air leak as the flanges vibrated after the blast. Since air normally contains 1% argon it can confuse the leak test results. In retrospect, it appears that the carbon monoxide and hydrocarbons from the blast may be good tracers for leakage. However, their initial concentrations are not controlled, so that the absolute calibration of leakage is not achieved like that with the argon tracer gas.

Following the blast tests, the vessel was carefully taken apart to look for signs of leakage. No visible external leakage was found, but there were some dark areas on the port surfaces where the steel plugs rubbed against the aluminum ports because of vessel vibrations during the blast. We swiped these dark areas seen in Figures 4, 5, and 6 and sent them for spectral analysis. Aluminum particulates from wear were seen everywhere, as one might expect, but vaporized copper from an electrode inside the vessel was only seen to pass the first two O-rings in Figures 7 and 8. Likewise, the signs of blast combustion products did not pass beyond the first two seals.

Figure 4. The bore of the top port showing abrasion of aluminum and leakage past the first two O-rings seals

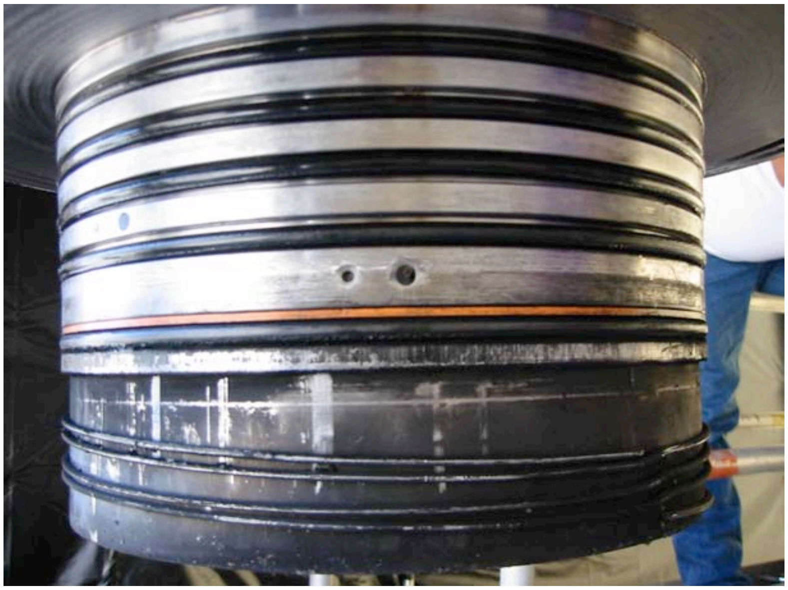

Figure 5. The top plug with sampling ports between the O-rings and evidence of particulate leakage past the first and second seals.

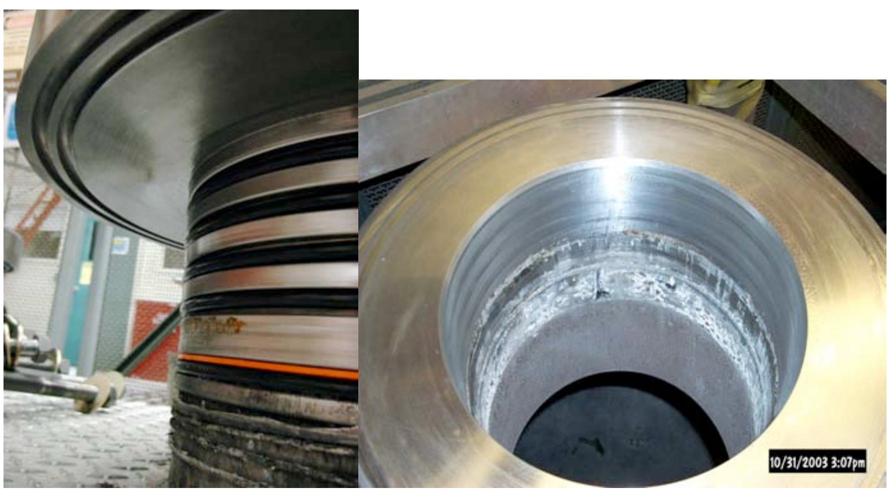

Figure 6. Leakage for the bottom plug was very similar to that on the top.

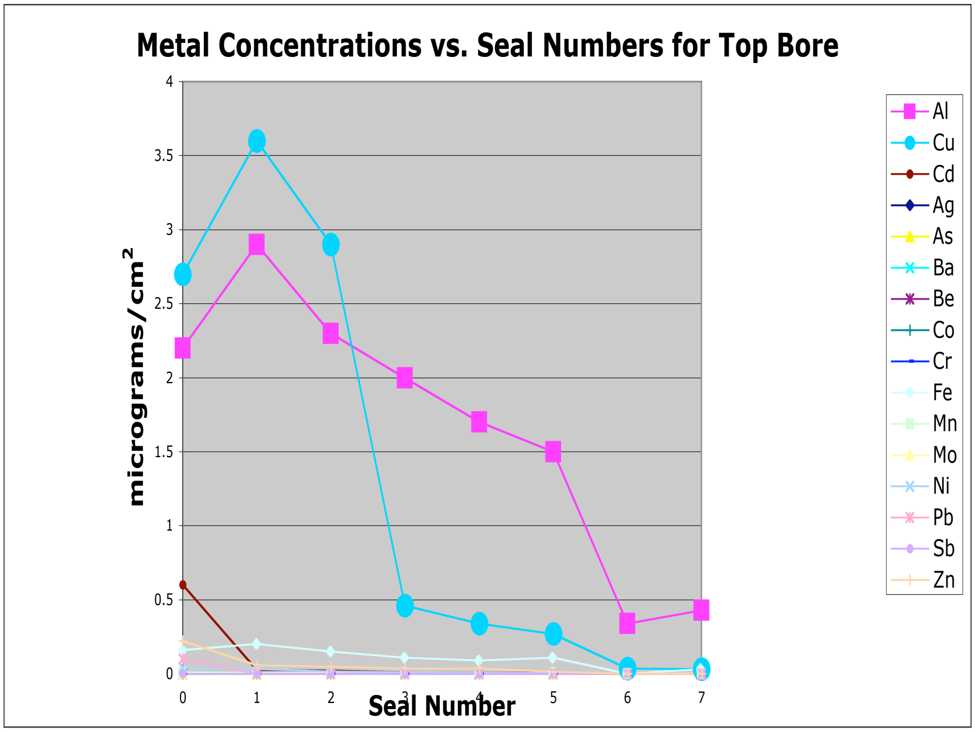

Figure 7. The vaporized copper from an internal electrode leaked passed the first two O-rings.

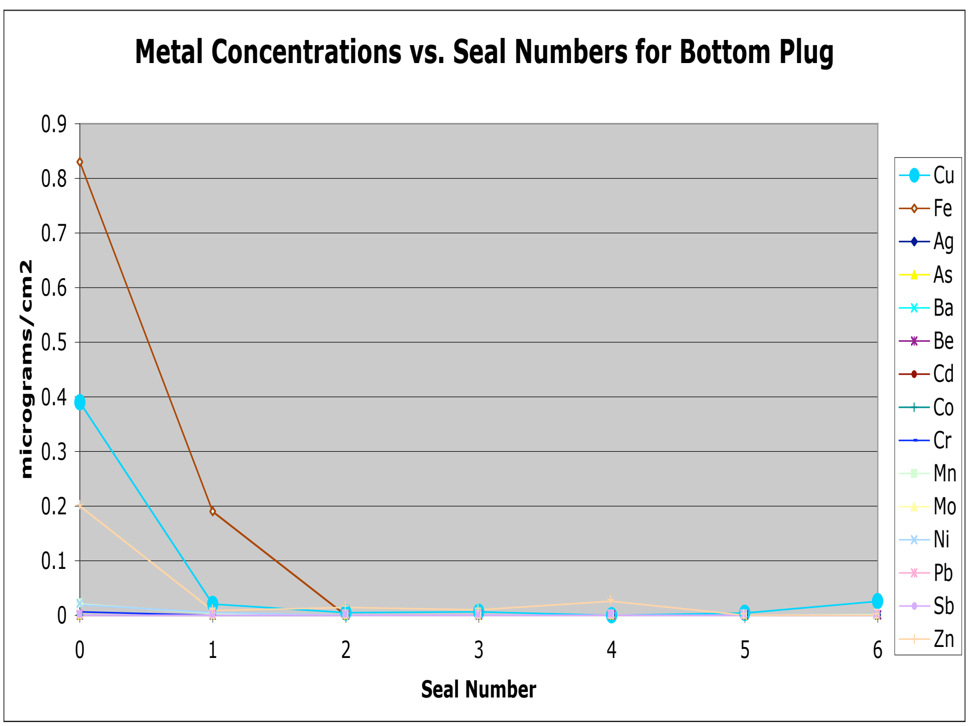

Figure 8a. Analysis of the metal particulates on the bottom plug also indicated that leakage occurred past the first two O-ring seals, but not further.

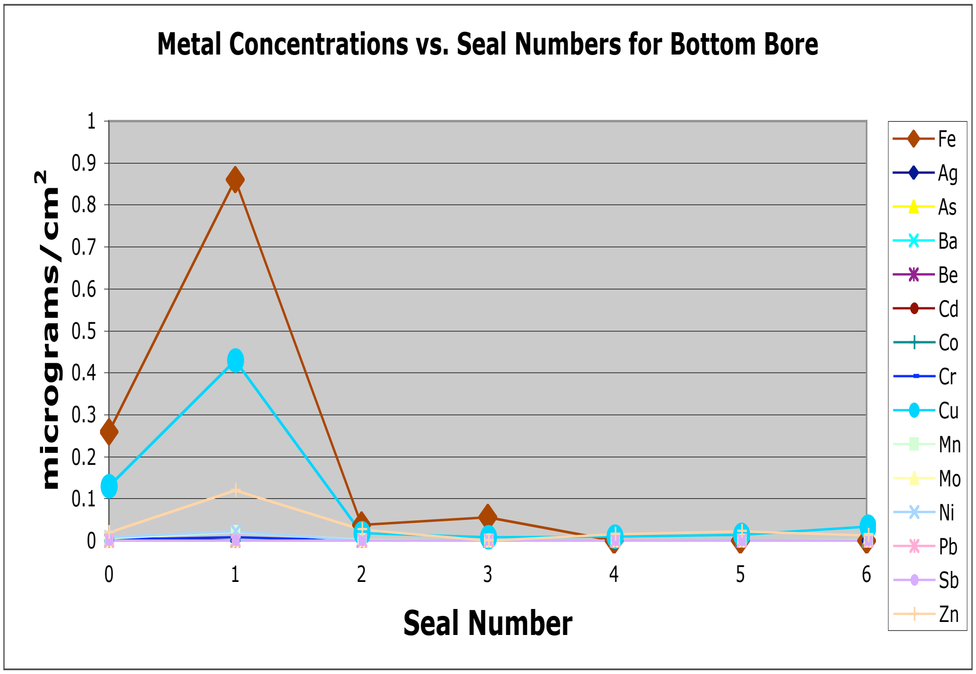

Figure 8b. Analysis of the metal particulates on the bottom bore also indicated that leakage occurred past the first two O-ring seals, but not further.

CONCLUSIONS

After many years of development it now appears possible to construct filament wound blast containment vessels that are light in weight and optically thin to X-rays or protons. Port seals can be kept leak tight by the use of redundant seals so as to meet strict environmental and safety standards comparable to those used for nuclear shipping containers. These same design techniques can be applied to other containment vessels and to personnel shields subject to blast conditions.

REFERENCES

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2) Curren and Bond, "Leakage of Radioactive Powders from Containers", *Proceedings of the Sixth International Symposium on Packaging and Transport of Radioactive Materials, West Berlin, Germany pp. 463-471 (1984)*
3) Grundler, Test Procedure for O-ring Interspatial Volume Test on CVD-2, LLNL report ERD03-167-AA (Nov. 11, 2003)